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Achieving High Resolution Measurements Within Limited Bandwidth Via Sensor Data Compression

by Michael Don and Tom Harkins

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Aberdeen Proving Ground, MD 21005-5066

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REPORT DOCUMENTATION PAGE

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
June 2013	Reprint	1 May 2012–1 September 2012

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Achieving High Resolution Measurements Within Limited Bandwidth Via Sensor Data Compression	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Michael Don and Tom Harkins	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
U.S. Army Research Laboratory ATTN: RDRL-WML-F Aberdeen Proving Ground, MD 21005-5066	ARL-RP-444

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

14. ABSTRACT

The U.S. Army Research Laboratory (ARL) is developing an onboard instrument and telemetry system to obtain measurements of the 30-mm MK310 projectile's in-flight dynamics. The small size, high launch acceleration, and extremely high rates of this projectile create many design challenges. Particularly challenging is the high spin rate which can reach 1400 Hz at launch. The bandwidth required to continuously transmit solar data using the current method for such a rate would leave no room for data from other sensors. To solve this problem, a data compression scheme is implemented that retains the resolution of the solar sensor data while providing room in the telemetry frame for other measurements.

15. SUBJECT TERMS

solar sensor, onboard instrumentation, data compression, sensor, telemetry, small and medium caliber gun-launched projectiles, MIDAS, high-g accelerometer

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Michael Don
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU	16	19b. TELEPHONE NUMBER (Include area code) 410-306-0775
Unclassified	Unclassified	Unclassified			

ACHIEVING HIGH RESOLUTION MEASUREMENTS WITHIN LIMITED BANDWIDTH VIA SENSOR DATA COMPRESSION

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ABSTRACT

The U.S. Army Research Laboratory (ARL) is developing an onboard instrument and telemetry system to obtain measurements of the 30mm MK310 projectile's in-flight dynamics. The small size, high launch acceleration, and extremely high rates of this projectile create many design challenges. Particularly challenging is the high spin rate which can reach 1400 Hz at launch. The bandwidth required to continuously transmit solar data using the current method for such a rate would leave no room for data from other sensors. To solve this problem, a data compression scheme is implemented that retains the resolution of the solar sensor data while providing room in the telemetry frame for other measurements.

KEY WORDS

Solar Sensor, Onboard instrumentation, Data compression

INTRODUCTION

Various projectile programs are underway in the U.S. Army to develop medium caliber precision munitions that will increase our warfighters' lethality and survivability while at the same time limiting collateral damage. In support of one such program, the U.S. Army Research Laboratory (ARL) has been tasked with obtaining on-board measurements of the 30mm MK310 projectile's in-flight dynamics from launch through impact. The small size, high loads (70 Kg launch), and extreme rates of this gun-launched, spin-stabilized projectile make this a challenging endeavor. An onboard telemetry instrumentation system has been designed to make the required measurements while preserving the MK310's form factor and physical characteristics.

This onboard instrument and telemetry system includes a rechargeable battery, S-band transmitter, antenna, signal conditioning circuitry, Field-programmable gate array (FPGA) based encoder, and various sensors. Solar sensors are used to make critical angular measurements. The spin rate of the MK310 is so high (up to 1400 Hz at launch) that the bandwidth required to continuously transmit solar data would leave no room for data from the other sensors. To solve this problem, a data compression scheme is implemented that retains the resolution of the solar sensor data while providing room in the telemetry frame for other measurements.

First a brief overview of the instrumentation system is given. Next, solar measurement requirements are explained in detail, leading to the telemetry bandwidth problem caused by the projectile's high spin rate. Finally, a solar data compression scheme that solves this problem is presented.

INSTRUMENTATION SYSTEM

Figure 1 shows a block diagram of the MK310's instrumentation system. The round is divided into two sections. The front section houses the antenna, transmitter board, and two solar sensors. The back section contains the instrumentation boards and battery power. 21 pin MDM connectors link the two sections together, providing signal routing between the sections when connected, as well as an external interface when the sections are separated.

The instrumentation boards are a miniaturization of the Multifunctional Instrumentation and Data Acquisition System (MIDAS) designed by ARL and detailed in several technical reports (1). The original MIDAS has a diameter of 1.4 inches and height of 1.6 inches. This miniaturization for a 30mm round is significantly smaller, with a diameter of 0.856 inches and height of 0.9 inches. Although these dimensions created design challenges, a wide variety of sensors were able to be integrated into the design. Table 1 lists the sensors contained on each board along with other pertinent information. Figure 2 shows a picture of completed individual encoder and configuration boards and a picture of an assembled encoder/configuration unit.
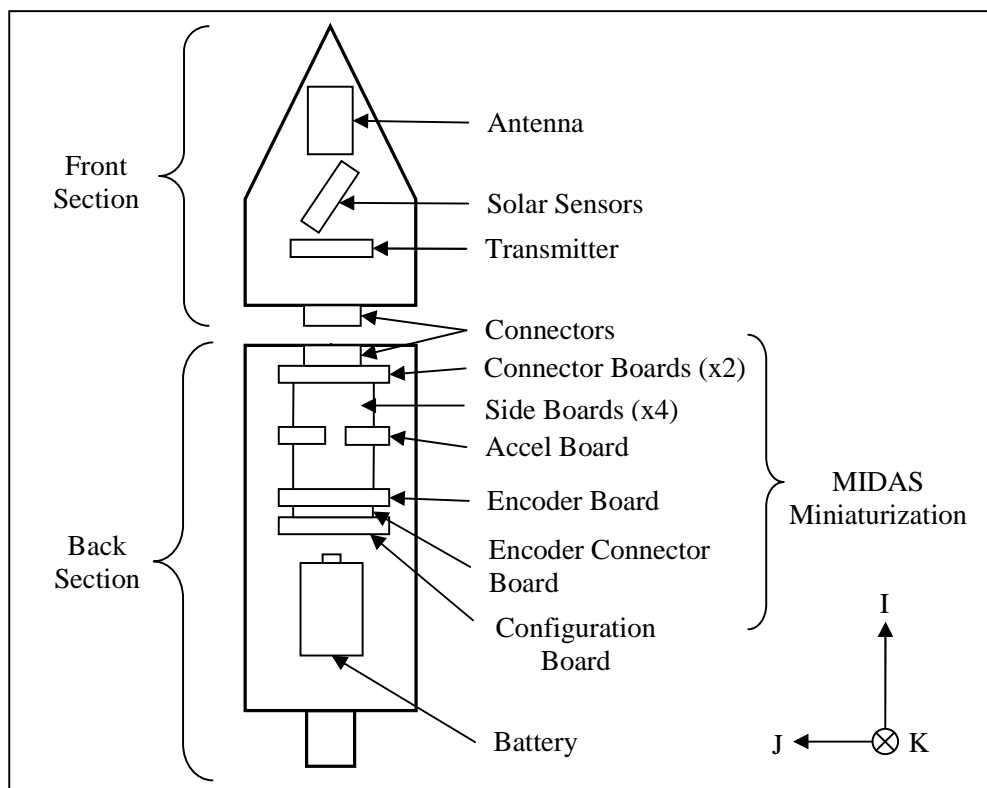

Figure 1. Block diagram of the instrumentation for the MK310.

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Table 1. 30mm MIDAS board descriptions

| Board	Description
Configuration	High-G Accel I, Battery Monitor, A/D, Signal conditioning/routing
Encoder connector x2	Combines configuration and encoder boards into a standalone unit
Encoder	FPGA based PCM encoder, SRAM
Side Sensor x2	Accelerometer I, Rate Sensor (J or K) , Signal routing
Accel	Accelerometer J/K, High-G Accelerometer J1/2 K1/2, Rate Sensor I
Side Power	3V/5V power regulation
Side Mag	Magnetometer I/J/K,
Connector	Battery Protection, G-Switch, Enable circuitry
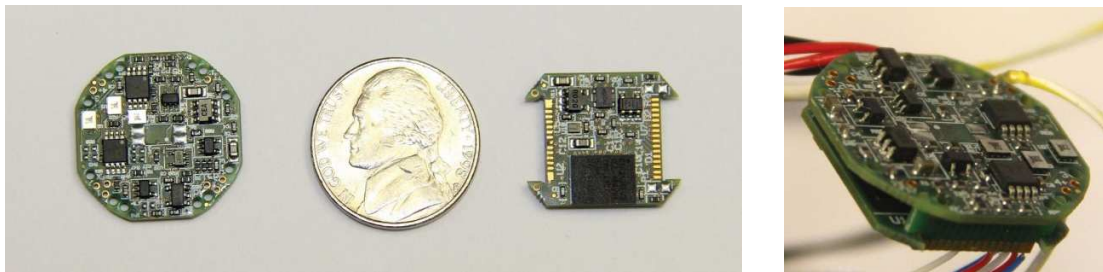
Figure 2. Encoder and configuration boards

SPIN AND YAWING RATE MEASUREMENTS USING SOLAR SENSORS

It is critical to consider the anticipated dynamics of planned flight experiments and their effects on the operation of sensors in order to successfully design an instrumentation system capable of achieving the desired measurements. Measurements of the angular motions of the MK310 projectile throughout its flight are required in the current Army program. This projectile will have an approximately Mach 3 launch velocity and 1400 Hz initial spin rate. At impact, the rates are approximately Mach 1 and 1000 Hz respectively.

There are four types of sensors included in the MIDAS suite that can be used for estimating projectile spin and yawing rates; accelerometers, rate sensors, magnetometers, and solar sensors (2). However, at spin rates of better than 1000 Hz, both the accelerometers and the rate sensors will be unable to provide measurements due to saturation of the devices from being out of range and/or from cross-axis sensitivity. Because the inventory MK310 projectile includes magnetizable materials, onboard magnetometer measurements of the Earth's magnetic field will be corrupted by spin-induced, body-fixed magnetic fields. Magnetic spin rate measurement should still be possible but magnetometer output will likely not be usable for yawing motion measurements (2). At this point only solar sensing remains as a potentially viable yaw measurement methodology.

Solar sensings are acquired using ARL patented devices (3) called solar light indicating transducers (SLITs). Simplistically, a SLIT might be likened to a box with a hole in its top and a

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sensing element in its bottom, i.e., a photovoltaic substrate. See Figure 3. Whenever the box is oriented such that light comes in the hole and strikes the photocell, a voltage is produced. SLITs are designed to have a small field of view (FOV) in the projectile roll direction and a large FOV in the perpendicular direction. As the projectile rotates, the sweeping of the SLIT FOV past the sun creates a pulse within a sequential record of the SLIT output. When two or more SLITs are used, the spacing of pulses can be processed to determine the included angle (σ) between the projectile spin axis and the vector to the sun. This spacing metric is called a solar ratio. Figure 4 shows sensor output from a 2011 flight experiment of a slowly rolling projectile (~4 Hz) equipped with two SLIT sensors. The accuracy with which the location of the peak of the negative polarity SLIT#2 pulse can be determined between two successive positive polarity SLIT#1 pulse peaks (i.e., the current solar ratio) directly translates into the fidelity of the measurement of σ.
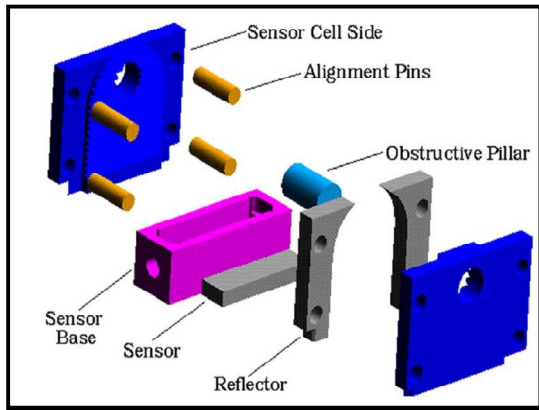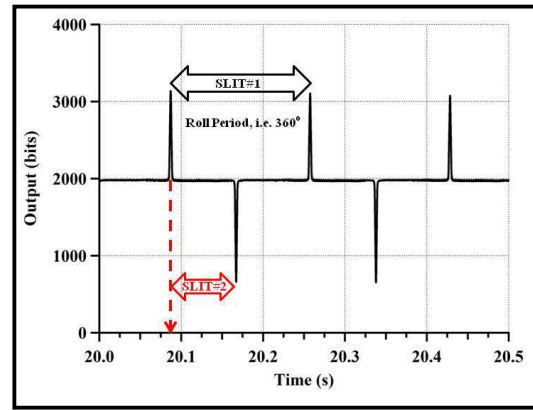

Figure 3. SLIT expoded view

Figure 4. Solar sensor flight data

Each pulse peak location is estimated as the mean of a Gaussian fit to the digitized sensor output across that pulse.   After installation of the SLIT sensors in a test projectile, laboratory calibration is performed to determine the solar ratio/σ relationship for that individual projectile to account for solar ratio variations arising from manufacturing and assembly tolerances.   For calibration purposes, these data are typically sampled at least every 0.1 deg of roll to achieve acceptable solar ratio/σ accuracy.   In-flight sampling intervals are functions of projectile spin rate and data acquisition system and telemetry system characteristics.

Figure 5 gives an example of the calibration data at σ=90 for the two SLIT projectile whose flight data are shown in figure 4. These calibration data, at 0.5 deg intervals, are seen as the red dots. The red line is the Gaussian fit through the calibration data. The black vertical line is the mean of the calibration data fit. Sampling at 5 deg intervals (blue circles), fitting these data (blue lines) to estimate peak locations, computing the solar ratio, and solving for σ results in an error of 2.34 deg.
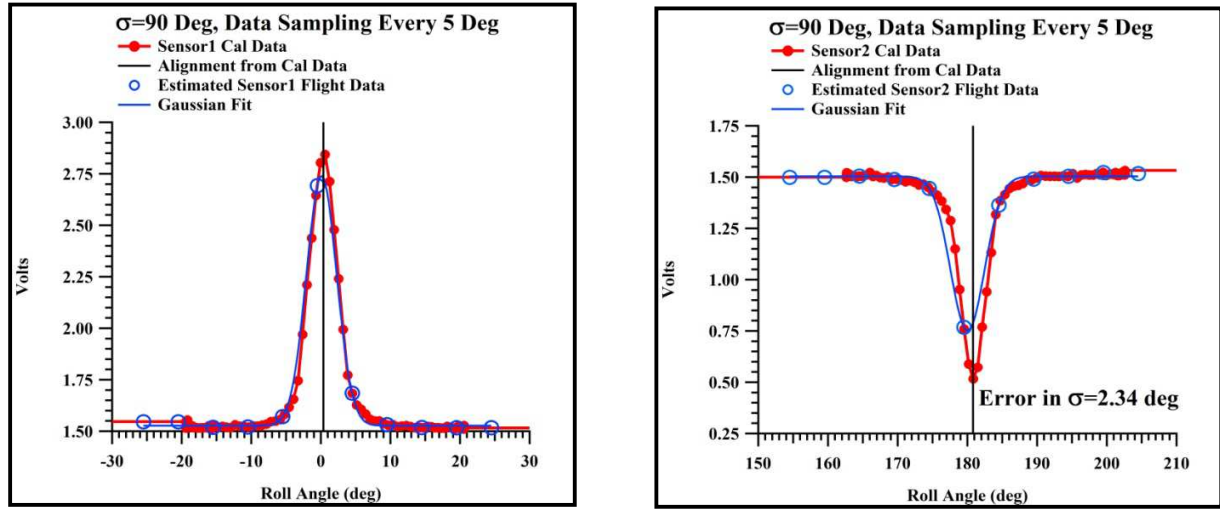
Figure 5. Calibration data and estimated flight data for two SLITs

Repeating this process at successively smaller in-flight sampling intervals, the resulting σ estimation errors are shown in Figure 6. This indicates that sampling intervals of no more than approximately 1.5 deg are necessary to achieve σ measurements of 0.1 deg accuracy. A 1.5 deg sampling interval corresponds to a 336 kHz sampling rate at the MK310 launch spin of 1400 Hz. At the same time, the 12-bit samples at a 4 megabit/s throughput yield a 333000 word/s telemetry rate. Thus, insufficient bandwidth exists to meet sampling requirements for the solar sensors, not to mention the other MIDAS sensors' output, the frame counters, and the telemetry sync words.
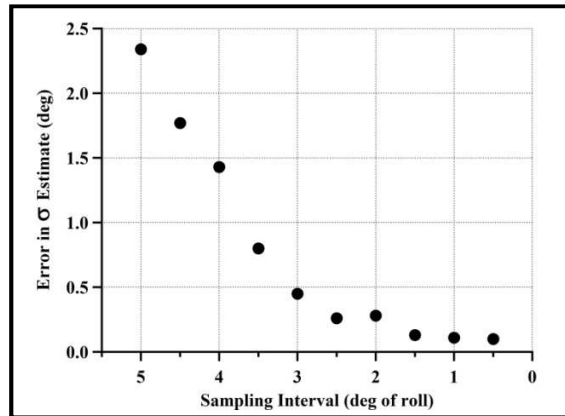

Figure 6. Measurement accuracy vs sampling interval

SOLAR DATA COMPRESSION

In order to increase the available bandwidth, a compression scheme was implemented for the solar data. The critical information contained in the solar data consists of the pulse peak times, which when using two solar sensors, occur twice per revolution. The most efficient method of transmitting the solar data would be to only transmit these peak times by calculating them on-board the projectile. It is impractical, however, to implement a curve fitting algorithm of sufficient accuracy to calculate these peak times using the low-power FPGA computing

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resources available. The next best approach is to capture and time stamp the samples around the peaks that make up the solar pulses while discarding the rest of the data. The actual peak times can then be calculated during post-processing using curve fitting algorithms to minimize error. Since the peaks are relatively narrow, this approach leads to a significant reduction in the amount of transmitted data.   `

Figure 7 shows a block diagram of this compression scheme. Analog sensor data are sampled at a high rate in order to provide sufficient resolution of the solar pulses. Other sensor data are sampled as well in these high speed frames and later buffered for transmission at a slower rate. Solar data are buffered separately and then saved when peaks are detected. The data are time stamped and inserted into a first-in, first-out (FIFO) buffer. This buffer empties into solar words in the final lower speed output frames for transmission. Sizes and rates of the high and low speed frames are defined so that they run synchronously.
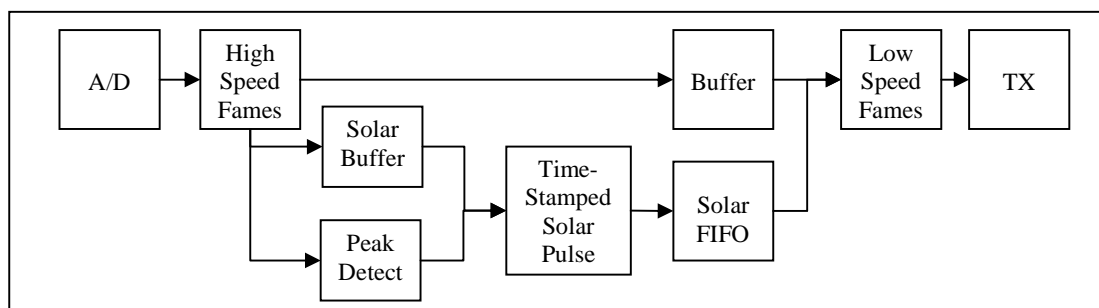

Figure 7. Solar data compression block diagram

An example telemetry frame design using this technique is implemented as follows. High speed frames composed of 60, 12-bit words are sampled at 10 Mbs, resulting in a 833 kHz sample rate. Solar data are sampled at every other word, giving a solar sampling rate of 417 kHz. Peak detection is performed on these high speed solar samples and only the 16 samples around the peak are saved. These samples are combined with 2 solar sync words and 2 time stamp words, and are buffered into a FIFO for insertion into the low speed frames for transmission. Assuming the maximum spin rate is 1400 Hz, with 2 solar pulses per revolution, the average solar word rate is 56 kHz. The final output frame is composed of 24, 12-bit words transmitted at 4 Mbs. This synchronizes the internal high speed frames to the slower output frames which both have a frame rate of about 14 kHz. 5 words of the output frame are sufficient to transmit the 56 kHz solar words, leaving 19 words for the other sensors, synchronization words, and frame counter. In summary, 417 kHz solar data that would have required 125% of the available telemetry frame now only consume about 20%, allowing for solar as well as other sensors to be included in the telemetry stream. Table 2 shows a summary of the statistics of this telemetry design.

Table 2. Solar compression frame summary

High Speed Bit Rate	10 Mbs	Words per Solar Pulse	20
High Speed Word Rate	833 kHz	Maximum Solar Word Rate	56 kHz
Words in High Speed Frames	60	Output Bit Rate	4 Mbs
High Speed Frame Rate	14 kHz	Words in Output Frame	24
Solar Sample Rate	417 kHz	Output Frame Rate	14 kHz
Maximum Solar Pulse Rate	2800 Hz	Solar Words per Output Frame	5

The essence of this solar compression technique is identifying the peak solar samples. If the solar output is well defined a simple peak detection algorithm is sufficient. Figure 8 shows a diagram of a simple peak detection algorithm. Starting at the Threshold Detect state, if the solar signal goes above the positive peak threshold, the Save Max state is entered, and the sample is saved as a maximum. Each successive sample is checked. If it is greater than the saved maximum, it is saved as the new peak maximum, otherwise it is ignored. Once the signal dips below the threshold, the saved value is confirmed as the peak value and the Threshold Detect state is re-entered. Some hysteresis is added to the thresholds to increase robustness to noise. A similar procedure in repeated for negative pulses using Save Min to identify minimum peaks. Figure 9 shows the results of this peak detection algorithm on well defined data. These solar data were taken from an actual munitions test and resampled to simulate a maximum 1400 Hz roll rate.
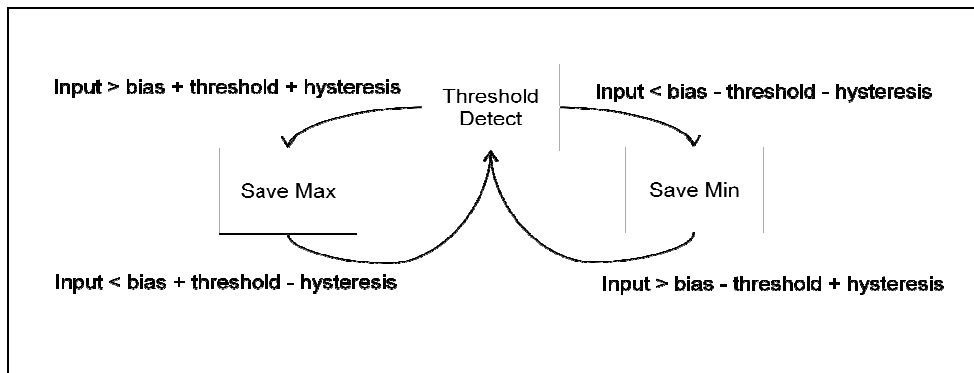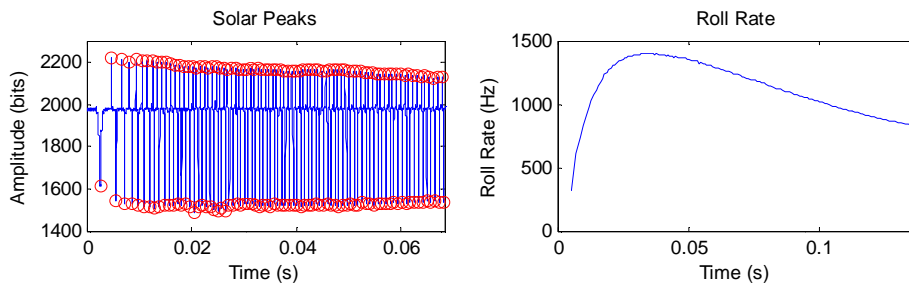

Figure 8. Simple peak detection diagram

Figure 9. Simple peak detection on well defined data

Although this simple peak detection algorithm works for well defined signals, there have been instances of solar signals from flight tests that have unusual noise characteristics. Figure 10 shows the solar data from a mortar flight test which exhibits large fluctuations in pulse amplitude. In some of the flight data, repeatable notches occurred in the peaks as seen in Figure 11. The simple peak detection algorithm incorrectly identified some of the peaks caused by these notches. It also missed some of the negative peaks that were severely attenuated. In order to increase the robustness of this compression scheme, a more complex peak detection algorithm was implemented. This algorithm could then also be used on other projectile programs to create a rough onboard roll angle estimate.
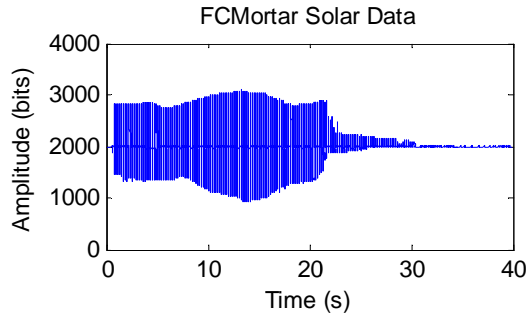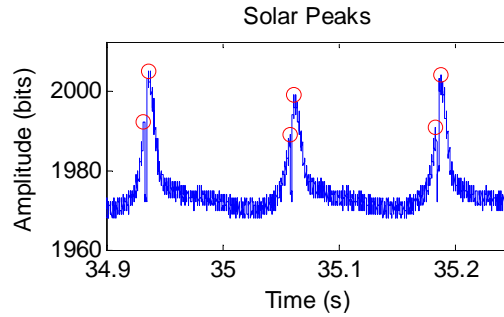
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Figure 10. FCMortar noisy solar data

Figure 11. Simple peak detect on noisy data

Figure 12 shows a block diagram of this new algorithm. Starting in the Save Max state, the first sample is automatically saved as a maximum. At each iteration, the new sample is checked against the current maximum. If it is larger, it becomes the new maximum, otherwise it is ignored. A threshold value is dynamically updated to be 25% of the peak to peak amplitude below the current maximum value. When the samples drop beneath this threshold, the maximum value is buffered and the same procedure begins to look for a minimum. Buffered peaks are checked at each iteration from the Save Max and Save Min states. If a specified time window elapses, the buffered peak is confirmed as a real peak and saved. If a new peak is found before the time window elapses, the new peak replaces the old buffered peak. Buffering the peaks and using a time window has the effect of using only the last peak if a few peaks are detected in quick succession. This removes false peaks due to the notch in the solar pulses seen in Figure 11. Each time a minimum or a maximum are detected, the peak to peak amplitude used in the threshold calculation is updated. This increases the algorithms noise immunity by updating the thresholds dynamically during flight, rather than relying on a predefined constant. A predefined bias value is also unnecessary since the threshold is measured from the maximum and minimum values which are also calculated during flight. Figure 13 shows this more complex peak detection algorithm successfully identifying positive and negative peaks in a noisy solar signal.
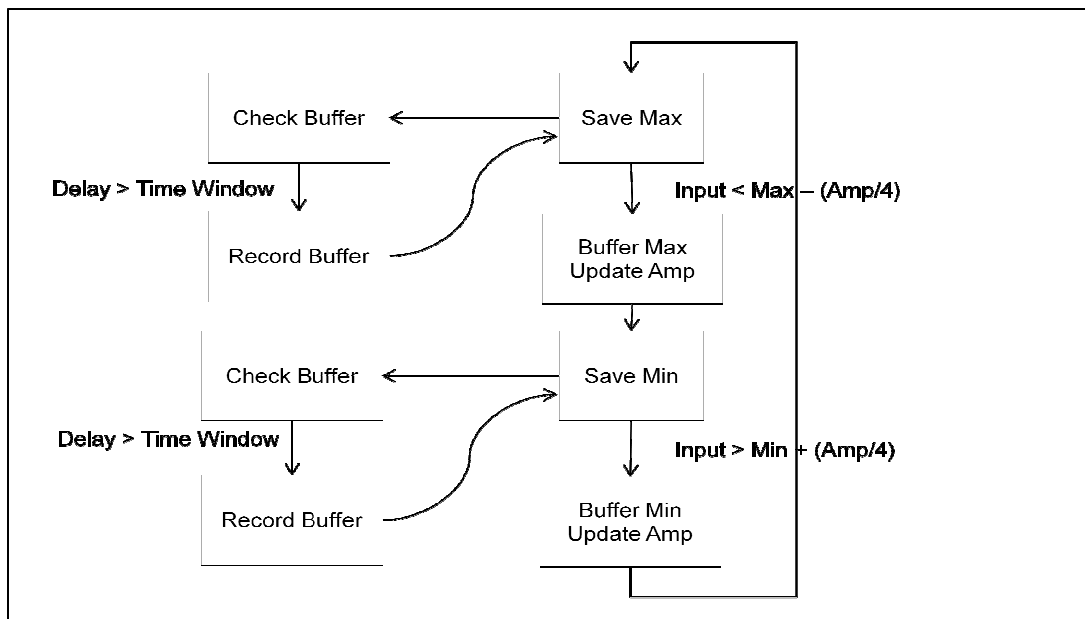

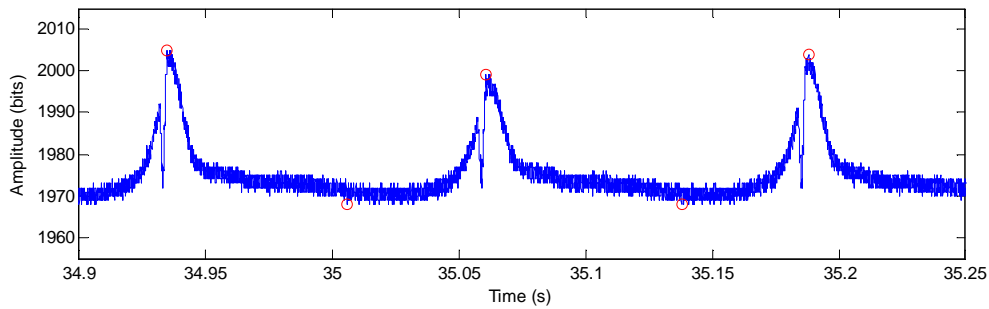**Figure 12. Complex peak detection**

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Figure 13. Complex peak detection on noisy data

Testing is planned in three stages. First the PCM encoder unit will be verified along with the hardware description language (HDL) code that implements the solar compression technique by using simulated solar data. Next the additional sensor electronics will be tested using real input from an outdoor spin test. Finally, the instrumentation system will be used to collect data from a real flight test. To date, only the first stage of testing has been completed.

The resampled flight data shown in Figure 9 were used as simulated solar data for laboratory testing. They were converted to a LabVIEW binary format and output at 500 KHz using a NI USB-6259 DAQ. This file was fed into an analog sensor input in the assembled encoder unit shown in Figure 2, encoded into the PCM stream, and output using a M/A COM 2255.5 MHz FM transmitter. Data were captured using a JDA VuSoft DECOM system and saved for post processing. Figure 14 shows example solar pulses captured by the PCM encoder and displayed relative to their decoded timestamps. The error in roll angle between the simulated solar data and the post-processed compressed data for 150 peaks is shown in Figure 15. Timing between the supplied test signal and the received signal was aligned by shifting the signals to minimizing the mean squared error. The minimal errors shown verify the implementation of the solar data compression scheme, and are likely due to electrical noise, quantization errors, and clock jitter.
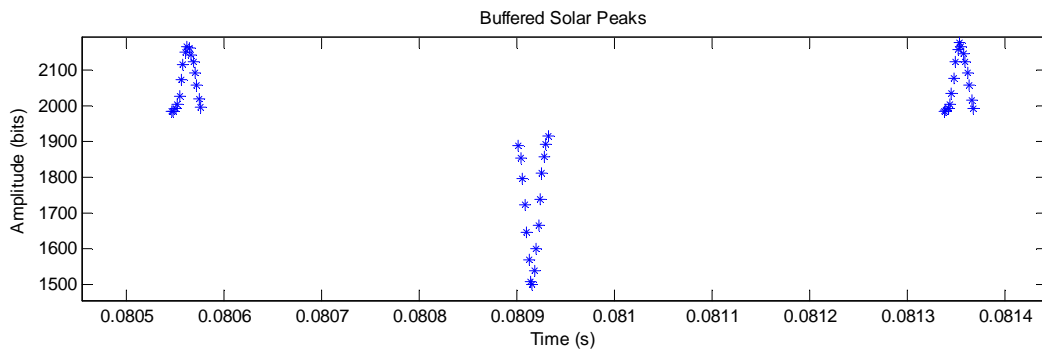

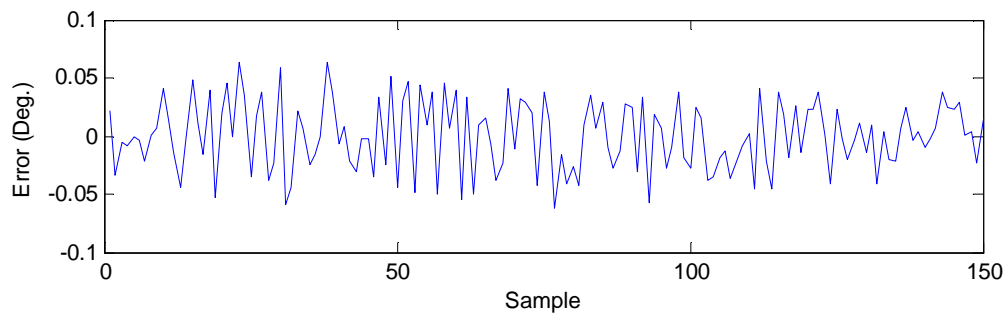**Figure 14. Solar telemetry data**

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Figure 15. Solar roll angle error

CONCLUSION

Designing an onboard telemetry instrumentation system for the 30mm MK310 posed many design challenges. Particularly challenging was the high spin rate which can reach 1400 Hz at launch. The bandwidth required to continuously transmit solar data for this spin rate leaves no room for data from other sensors. To solve this problem, a data compression scheme was designed that retains the solar sensors' resolution while providing room in the telemetry frame for other measurements. The design was successfully verified through laboratory simulation, and flight tests are planned in the future. Besides enabling measurements for the MK310, this design will enhance the telemetry capability of all of ARL's programs that use solar sensors.

ACKNOWLEDGEMENTS

We would like to thank our co-workers at ARL for their contributions to the 30mm project:

Peter Muller – original MIDAS design
Rex Hall – antenna design
David Grzybowski – mechanical design
Brad Davis – sensor selection

Steve Buggs – part assembly
Mark Ilg – solar sensor noise consultation
Barry Kline – circuit board photographs

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